Molecular Gas in Candidate Double Barred Galaxies III. A Lack of Molecular Gas?

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ABSTRACT

Most models of double-barred galaxies suggest that a molecular gas component is crucial for maintaining long-lived nuclear bars. We have undertaken a CO survey in an attempt to determine the gas content of these systems and to locate double barred galaxies with strong CO emission that could be candidates for high resolution mapping. We observed ten galaxies in CO J=2−1 and J=3−2 and did not detect any galaxies that had not already been detected in previous CO surveys. We preferentially detect emission from galaxies containing some form of nuclear activity. Simulations of these galaxies require that they contain 2 to 10% gas by mass in order to maintain long-lived nuclear bars. The fluxes for the galaxies for which we have detections suggest that the gas mass fraction is in agreement with these models requirements. The lack of emission in the other galaxies suggests that they contain as little as 7×10^6 $M_\odot$ of molecular material which corresponds to $\lesssim$0.1% gas by mass. This result combined with the wide variety of CO distributions observed in double barred galaxies suggests the need for models of double-barred galaxies that do not require a large, well ordered molecular gas component.

Subject headings: Galaxies: nuclei — galaxies: active

1. Introduction

Double-barred galaxies have been proposed as a means of transporting molecular gas interior to inner Lindblad resonances (ILRs) where it may fuel starbursts or other forms of nuclear activity (Shlosman, Frank, & Begelman 1989). Thus far, double-barred galaxies have been identified predominantly through the analysis of near infrared (NIR) images (e.g. Mulchaey, Regan, & Kundu 1997) and manifest themselves as variations in the position angles and ellipticity with galactic radius. A variety of models have been proposed to explain the nature of these nuclear bars, with origins varying from kinematically distinct nuclear bars to nuclear agglomerations that co-rotate at the same speed as the large scale bar (Friedli & Martinet 1993; Shaw et al. 1993). To allow long-lived nuclear bars, these models usually require substantial amounts of dissipative gas to prevent the nuclear stellar populations from suffering rapid kinematic heating and subsequent bar destruction.

There is another class of models that attempt to explain nuclear bars using purely stellar orbits. It is known that there are different classes of orbits in a barred potential. The two important ones are

the x_1 family that runs parallel to the bar major axis, and the x_2 family that runs perpendicular to it (e.g., Athanassoula 1992). It was thought that the x_2 orbits of the large scale bar near the nucleus could form the x_1 orbits of the smaller nuclear bar and the corotation radius of the nuclear bar could correspond to the ILR of the large scale bar. In this picture, the nuclear bar must *always* be aligned perpendicular to the main bar. Friedli & Martinet (1993) rule out this model by studying a large sample of double-barred galaxies, since they found that not all the observed offset angles between the nuclear bar and the main bar can be explained by inclination effects. Recently, Maciejewski & Sparke (2000) find that there exist orbits in which particles in a double-barred potential (where the inner bar rotates faster than the large scale bar) remain on closed orbits and may form the building blocks of long-lived double-barred galaxies without the need for a gaseous component.

High resolution observations of the dynamics of these galaxies will allow us to test these competing models and learn the true nature of nuclear bars. Of the currently known double-barred galaxies, only a few have been studied in detail using high resolution observations of the molecular gas (e.g. Petitpas & Wilson 2002; Jogee, Kenney, & Smith 1999). In Petitpas & Wilson (2002; hereafter Paper I) we used high resolution CO observations to compare the molecular gas distributions of two candidate double-barred galaxies to the models of Friedli & Martinet (1993) and Shaw et al. (1993). We found that in NGC 2273 the molecular gas emission takes the appearance of a bar-like feature that is aligned with the NIR isophote twists. In NGC 5728, we observed a rather disorderly molecular gas morphology that did not align with the NIR morphology, nor did it align with any features seen at other wavelengths in the nuclei of this galaxy.

The similarity in the NIR images of these galaxies suggests that the galactic potentials may be similar. The variety of molecular gas morphologies suggests that the molecular gas may have different properties in each galaxy allowing it to respond differently to these similar potentials. In Petitpas & Wilson (2003; hereafter Paper II) we performed a multi-transition CO survey of the nuclei of double barred galaxies for which high resolution CO maps exist. We found that the molecular gas was cooler (and less dense) in galaxies with more centrally concentrated gas distributions and warmer and denser in galaxies with CO emission scattered about the nucleus. The star formation rates in the galaxies with non-centrally concentrated gas distributions tended to be higher than in the galaxies with strong central concentrations. This result suggests that either the gas distribution is influencing the star formation activity, or that the star formation may be affecting the gas properties.

The seven galaxies discussed in Papers I and II represent a small fraction of the total number of galaxies known to have nuclear bars (as indicated by NIR isophote twists). In order to strengthen the hypotheses of those papers, we need to study a larger sample of galaxies. Of the 93 galaxies studied to date (Jarvis et al. 1988; Shaw et al. 1993; Wozniak et al. 1995; Elmegreen et al. 1996; Mulchaey, Regan, & Kundu 1997) only 23 contain isophote twists with size scales and position angle offsets large enough to be resolved by the Caltech Millimeter and BIMA Arrays. Since the larger NIR surveys mentioned above were performed using southern observatories, most of the candidates are located in the southern hemisphere. Of those 23 galaxies with resolvable bars, only 13 are at a declination $> -30°$. Six of these (NGC 470, NGC 2273, NGC 4736, NGC 5850, NGC 5728, and NGC 6951[1]) have high resolution CO maps published (Paper I; Jogee 1998; Wong & Blitz 2000; Leon, Combes, & Friedli 2000; Kohno, Kawabe, & Vila-Vilaró 1999). Only NGC 3945 was not included in our sample due to time and source availability constraints.

We have performed a CO survey of the nuclei of 10 galaxies known to have strong NIR isophote twists in an attempt to find CO-bright double barred galaxies that would make good candidates for high resolution mapping. Five of these galaxies (NGC 2273, NGC 3081, NGC 4736, NGC 5728, and NGC 6951) are discussed in detail in Papers I and II. In §2 we discuss the observations and data reduction techniques. In §3 we discuss our detections (and non-detections) in more detail, and compare our observations to previous studies of

[1] More recent studies suggest that NGC 6951 does not currently contain a nuclear bar, but may have had one in the past (Pérez et al. 2000). See §3 for more details.

these galaxies. We also determine the molecular gas masses, and discuss the implications of these masses to the double barred galaxy models. This work is summarized in §4.

2. Observations and Data Reduction

2.1. NRAO Spectra

The nuclei of nine double barred galaxies were observed in ^{12}CO J=2−1 using the National Radio Astronomy Observatory (NRAO)[2] 12-m Telescope. Observations were taken in remote observing mode over a 14 hour period on 15 February, 2000. The half-power beam width of the NRAO 12-m was 29″ at 230 GHz (^{12}CO J=2−1). All observations were taken in 2IF mode with the Millimeter AutoCorrelator (MAC). The pointing was found to be accurate to 6″ for the first half of the evening when we observed our galaxies with NGC $<$ 4736. This is poorer than the normal value for the NRAO 12-m, likely due to the high winds. In the second half of the evening the winds diminished, and the pointing improved to the more normal value of 5″ for observations of galaxies with NGC $\geq$ 4736. The calibration was also monitored by observing spectral line calibrators and planets and the spectral line calibrators agreed with the published values. Thus, we adopt the nominal main beam efficiency from the NRAO Users Guide of 0.29 at 230 GHz.

2.2. JCMT Spectra

Previous CO studies of double barred galaxies show CO J=3−2/J=2−1 line ratios $\gtrsim 1$ (Paper II) so for galaxies that were not detected with the NRAO Telescope, we obtained higher resolution ^{12}CO J=2−1 and ^{12}CO J=3−2 spectra using the James Clerk Maxwell Telescope (JCMT)[3]. These observations were taken over the period of 1999 - 2000, mostly as part of a bad weather backup project. The half-power beam width of the JCMT is 21″ at 230 GHz (^{12}CO J=2−1) and 14″ at 345 GHz (^{12}CO J=3−2). All observations were obtained using the Digital Autocorrelation Spectrometer. The calibration was monitored by frequently observing spectral line calibrators. The spectral line calibrators showed very little scatter from the published values with individual measurements differing by typically $<$ 15% from standard spectra. Thus, we adopt the nominal main beam efficiencies from the JCMT Users Guide of 0.69 at 230/220 GHz and 0.63 at 345 GHz. A detailed observing summary for the JCMT and NRAO observations is given in Table 2.

2.3. Reduction

Similar data sets were averaged together using the software package SPECX for the JCMT data and the Bell Labs data reduction package COMB for the NRAO data. The data were binned to 10 km s^{-1} resolution (7.7 and 11.5 MHz at 230 and 345 GHz, respectively) and zeroth or first order baselines were removed. The emitting regions we detected were quite wide ($>$ 300 km s^{-1}) but the spectrometer bandwidth was 800, 800, and 1200 km s^{-1} for the NRAO and JCMT J=3−2 and J=2−1data, respectively, which allowed for accurate baseline determination. For the galaxies where we have no detections, the baseline levels were set using the region of the spectrometer outside a 400 km s^{-1} range centered on the rest velocity of the galaxies (i.e. $V_{lsr} \pm 200$ km s^{-1}) in order to maximize our chances of detecting any weak signal. The NRAO spectra for each galaxy are shown in Figure 1 and the JCMT spectra are shown in Figure 2. In the cases where the NRAO spectra show no convincing detections, we have included when available the ^{12}CO J=2−1 spectra taken at the JCMT and published in Paper II (Figure 3). The spectral line intensities are summarized in Table 3.

Using the $T_{\rm R}^*$ temperature scale would ensure that our observed line strengths are as close to the true radiation temperatures as possible (Kutner & Ulich 1981). However, conversion to $T_{\rm R}^*$ from $T_{\rm A}^*$ requires knowledge of the forward scattering and spillover ($\eta_{\rm FSS}$), which is difficult to measure and was not attempted during the JCMT observing runs. On the other hand, we do have good values for the main beam efficiencies and so an accurate conversion to main beam temperature ($T_{\rm MB}$= $T_{\rm A}^{\star}/\eta_{\rm MB}$) is possible. Therefore, we will

[2]The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[3]The JCMT is operated by the Joint Astronomy Centre in Hilo, Hawaii on behalf of the parent organizations Particle Physics and Astronomy Research Council in the United Kingdom, the National Research Council of Canada and The Netherlands Organization for Scientific Research.

display our spectra using the main beam temperature scale. We report our fluxes in Table 3.

3. Discussion

3.1. Individual Galaxies

NGC 2273: The NRAO 12-m detection of this galaxy is not strong. Given the velocity width of the emission and the fact that all the emission is located in the central few arcseconds (Petitpas & Wilson 2002) the large beam of the 12-m dilutes the emission substantially.

We have JCMT CO J=2−1 and J=3−2 spectra with strong detections (Paper II, Figure 3) so despite the weak emission in the NRAO spectrum for this region we expect to see emission over the velocity range from 1600 to 2000 km s^{-1}. For completeness we include the ^{12}CO J=3−2 spectrum of this galaxy from Petitpas & Wilson (2003) in Figure 3.

NGC 2859: Despite our rather high sensitivity, this galaxy was not detected in ^{12}CO J=2−1 with the NRAO 12-m, nor in ^{12}CO J=3−2 with the JCMT. A literature search shows that it was detected with the 3.5′ beam of Arecibo and contains 2.1×10^8 M$_\odot$ of H I (Bieging & Biermann 1977; Wardle & Knapp 1986).

NGC 2950: Due to the similarity in LST with NGC 2859, we were unable to attempt an NRAO 12-m observation of this galaxy. It was observed with the JCMT but was not detected in ^{12}CO J=2−1. A literature search shows that H I was not detected in the galaxy (Wardle & Knapp 1986).

NGC 3081: We have JCMT CO J=2−1 spectra for NGC 3081 (Figure 3) that show emission over a region from 2200 to 2500 km s^{-1}, while in the NRAO spectrum, we see no detectable line. This is likely due to the high noise level in the NRAO spectra of NGC 3081 due to its low declination.

NGC 4340: No emission was detected in ^{12}CO J=2−1 with the NRAO 12-m, so followup observations were taken at the JCMT in ^{12}CO J=3−2 with the same result. This galaxy was not detected in H I with Arecibo (Giovanardi, Krumm, & Salpeter 1983).

NGC 4371: This galaxy is also not detected with the NRAO 12-m in ^{12}CO J=2−1, JCMT in ^{12}CO J=3−2, or Arecibo in H I (Giovanardi, Krumm, & Salpeter 1983).

NGC 4736: This nearby galaxy was easily detected with the NRAO 12-m in ^{12}CO J=2−1. The line profiles and peak strength for NGC 4736 agree well with those published in Paper II.

NGC 5728: The emission in NGC 5728 is known to cover a wide range of velocities from less than 2600 km s^{-1} to greater than 3050 km s^{-1} and is very clumpy (Petitpas & Wilson 2002; Schommer et al. 1988). The line would nearly cover the entire spectrometer which makes it difficult to determine the baseline for the spectra of NGC 5728 shown in Figure 1. We have used the very ends of the spectrometer to determine the baseline level, and the result is a lumpy spectra with no strong noticeable peaks, but a general tendency for the noise to remain slightly greater than zero. NGC 5728 is clearly detected in the JCMT spectrum shown in Figure 3.

NGC 5850: This galaxy is clearly detected in the NRAO 12-m spectrum. There are no published single dish CO spectra for NGC 5850 so we cannot compare line profiles. Single dish fluxes and interferometric maps are published in Leon, Combes, & Friedli (2000), and they find single dish gas masses comparable to ours, suggesting that our pointing and calibration are correct.

NGC 6951: The NRAO 12-m line profile of NGC 6951 (Figure 1) is single peaked which is noticeably different than the JCMT ^{12}CO J=2−1 spectrum for this galaxy (see Paper II). The profile of the NRAO spectrum more closely resembles the CO J=3−2 spectrum taken with the JCMT at an offset of (0″,−7″) as part of our 5-point mapping procedure discussed in Paper II. In addition to this, the peak line strength in the NRAO spectrum is much lower than the JCMT ^{12}CO J=2−1 spectrum, suggesting that pointing inaccuracies may have resulted in pointing the telescope too far south, missing the strongest emission in the northern part of the nucleus (Kohno, Kawabe, & Vila-Vilaró 1999) with the most sensitive part of the beam.

We also point out here that after the inclusion of this galaxy in our sample, more recent studies have suggested that it does not contain a double bar as indicated by the earlier NIR surveys. Pérez et al. (2000) find evidence that NGC 6951 may have contained a nuclear bar at one point, but gas

accumulation into the nucleus may have resulted in its dissolution. We choose to keep it in our sample since its presence does not affect any of our conclusions.

3.2. Cumulative Results

Despite our rather high sensitivity ($T_{\rm MB}$(rms) $\approx$ 14 mK) we have failed to detect CO J=2−1 lines in NGC 2859, NGC 4340, or NGC 4371. We do not detect any galaxies that have not been previously detected in the CO surveys of Braine & Combes (1992), Mauersberger et al. (1999), and Young et al. (1995). Looking at Table 1 suggests that we are predominantly detecting CO in later type galaxies, which is a result known from previous studies (Young et al. 1995), but there is also an apparent trend with nuclear activity.

Beside the galaxy names in Figures 1 and 2 are codes (in parentheses) that indicate the types of nuclear activity found in these galaxies. Seyfert 2s are marked as "S2" and LINERs are flagged with "L" (Ho, Filippenko, & Sargent 1997). Galaxies without any detected nuclear activity are not flagged and show no signs of Seyfert, LINER, or starburst activity. All of the galaxies that we have detected show signs of nuclear activity. Of the four galaxies that we have not detected in CO emission, none of them show any signs of nuclear activity[4]. We note that in performing a literature search, the galaxies that we have not detected are quite a bit less studied than NGC 4736 and NGC 6951, for example, and may harbor as yet undetected nuclear activity which could change our small number statistics noticeably.

3.3. Molecular Gas Mass

The double barred galaxy models of Friedli & Martinet (1993) and Shaw et al. (1993) suggest that there needs to be substantial amounts of molecular gas in double barred galaxies. In fact, the molecular gas inflow in these double barred galaxies may accumulate enough mass so that the nuclear bar can become kinematically distinct (Friedli & Martinet 1993; Pfenniger & Norman 1990). Thus, we may expect to see high molecular gas masses in the centers of these double barred galaxies.

[4]Ho, Filippenko, & Sargent (1997) gave NGC 2859 the uncertain classification of a "transition object", that is, a galaxy showing signs of both an H II and LINER nucleus. However, the lines are weak and the spectra are noisy.

The intensity of the CO emission can be related to the molecular mass using the equation

$$M_{\rm mol} = 1.61\times10^4 \left(\frac{\alpha}{\alpha_{\rm Gal}}\right)\left(\frac{115\ {\rm GHz}}{\nu}\right)^2 d^2_{\rm Mpc}\,\frac{S_{\rm CO}}{R}\ {\rm M}_\odot \qquad (1)$$

(Wilson & Scoville 1990; Wilson 1995) where $S_{\rm CO}$ is the ^{12}CO J=2−1 flux in Jy km s^{-1}, R is the ^{12}CO J=2−1/J=1−0 line ratio, ν is the frequency of the emission (230 GHz for the J=2−1 transition), $d_{\rm Mpc}$ is the distance to the galaxy in Mpc, α is the CO-to-H_2 conversion factor for that galaxy, and $\alpha_{\rm Gal}$ is the Galactic value ($3\pm1\times10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$, Strong et al. 1988; Scoville & Sanders 1987). We use 24.7 Jy K^{-1}, 27.8 Jy K^{-1} ($\eta_{\rm ap}$= 0.63, 0.56) and 70.6 Jy K^{-1} ($\eta_{\rm ap}$= 0.35) to convert our JCMT (J=2−1, J=3−2) and NRAO J=2−1 data (respectively) from Kelvins ($T^\star_{\rm A}$) to Janskys (Kraus 1986; JCMT Users Guide; NRAO 12-m Users Manual). We assume a coupling efficiency ($\eta_{\rm c}$) of 0.7 to correct our observed fluxes to true fluxes. The CO-to-H_2 conversion factor (α) is a globally averaged property of the galaxy and hence there are uncertainties involved in its use in one specific region of the galaxy and it is only accurate to within $\sim$ 30%. Our fluxes are typically accurate to about 10%. The distances for these relatively nearby galaxies are likely uncertain by at least 30%. We therefore adopt a total uncertainty of 50% in our mass estimates.

For the galaxies where we have CO detections with other telescopes or at other frequencies, we integrate over the velocity range where the emission line was seen. For galaxies with no previous detections, we integrate over a 400 km s^{-1} range centered on the rest velocity of the galaxy (this region was excluded from the baseline subtraction). In the cases where the integrated intensity is greater than the rms noise, we give both the integrated intensity and the noise regardless of how insignificant. We are not claiming these as detections, but are simply using them as a more realistic value for the detection cut-off limit. If the integrated intensity is less than or equal to the rms noise, the noise value is given as an upper limit. The results are summarized in Table 3.

Table 3 shows that there is a wide variety of molecular gas masses in the inner regions of these

galaxies. For the galaxies in our sample that have also been detected with the JCMT, we find that the masses determined here typically are lower or agree with the masses determined with CO J=2−1 data in Paper II within a factor of two. The exceptions are NGC 6951 which is lower here by more than a factor three and NGC 4736 which is higher by almost a factor of two. The discrepancy in NGC 6951 can likely be attributed to the pointing offset discussed in §3. The discrepancy in NGC 4736 can likely be attributed to the strong CO emission in the spiral arms falling in the larger beam of the NRAO telescope (Wong & Blitz 2000). In any case, the similarities between the masses obtained with the weaker NRAO 12-m spectra (even in the cases where no obvious lines are visible such as NGC 3081 and NGC 5728) and the masses obtained with the JCMT J=2−1 spectra gives us confidence that our mass estimates and upper limits are accurate to at least a factor of two.

Of particular interest is the galaxy NGC 5850, whose spectrum indicates that there is more than 10^9 $M_\odot$ of molecular gas in the inner 29″. This mass is comparable to the amount of molecular gas in the entire Milky Way, but now contained in its inner 2.5 kpc radius (Dame et al. 1993). The optical size of this galaxy is $4\rlap{.}'3 \times 3\rlap{.}'7$ ($D_{25} \times d_{25}$), which corresponds to 43×37 kpc at its distance of 34 Mpc. This clearly makes it the largest galaxy in our sample (the second runner up is NGC 5728 at 33×19 kpc). Given its rather strong primary bar, it is possible that the large quantity of gas in the inner regions of this galaxy may have been transported inward by the inflow mechanisms known to be associated with bar perturbations. The high resolution CO maps of this galaxy (Leon, Combes, & Friedli 2000) detect only 6.7×10^7 $M_\odot$ of molecular gas, mostly concentrated in a small off-center peak of emission approximately 8″ north of the galactic center. On the other hand, their single dish IRAM 30-m CO J=1−0 map of the entire primary bar detects 3.4×10^9 $M_\odot$. Leon, Combes, & Friedli (2000) point out that this galaxy is surprisingly quiescent given the large amounts of molecular gas, and propose that the reason for this is that the molecular gas is below the critical surface density for gravitational instabilities (Kennicutt 1989).

The large size of NGC 5850 and the fact that it is the only quiescent galaxy with a strong detection lead us to wonder if we are detecting emission lines in predominantly the largest galaxies (with possibly the largest molecular gas reservoirs). All the other galaxies are in the 15 to 20 kpc (major axis) size range with the exception of NGC 2859, NGC 5728, and NGC 5850 who have major axes of 28, 33, and 43 kpc respectively. The strongest line occurs in the closest galaxy, NGC 4736, which is incidentally one of the smallest in our sample with major axis of ∼14 kpc. So it seems that we are not detecting CO emission preferentially in larger galaxies. Since NGC 5850 is the second most distant galaxy in our sample, it also appears that we are not preferentially detecting emission from the closest galaxies.

Since we are searching for emission with the CO J=2−1 line, our lack of success in finding bright candidates may not be the result of a lack of molecular gas, but that the gas in these galaxies is very cool and possibly at a low density. Is it possible that all of the molecular emission is dominated by J=1−0 emission and it is not excited into the J=2−1 levels enough to be detected? In our mass calculation, we assume a J=2−1/J=1−0 line ratio of 0.7. In the Local Thermodynamic Equilibrium approximation, in order to achieve this line ratio, the gas must be at a temperature of only 7 K. This temperature is low enough that it can be maintained by cosmic ray heating (Goldsmith & Langer 1978). Higher values of the J=2−1/J=1−0 line ratio will act to decrease our molecular gas mass, meaning that the mass values quoted here are likely upper limits.

Another possible explanation for the low molecular gas mass may be that the gas is just not located in the inner 29″. There are observations of other galaxies that contain large molecular rings that seem to have prevented any of the molecular gas from reaching the nucleus (e.g. NGC 7331; Sheth 2000). We will need spectra covering a wider field of view to verify if this is happening in any of these galaxies.

3.4. Implications for Double Barred Galaxy Models

All the galaxies in this survey are known to contain the NIR isophote twists believed to be the signature of a double barred galaxy. As mentioned in §1, the models of double barred galaxies by Shaw

et al. (1993) and Friedli & Martinet (1993) require large amounts of molecular gas in the nuclear regions of these galaxies in order to sustain long-lived double bars. The gas requirements vary from 4 to 6% globally (Shaw et al. 1993; Friedli & Martinet 1993) to as little as 2% in the nucleus (Friedli & Martinet 1993). This gas is required to provide the dissipation needed to prevent the stellar component from dynamically heating so much that the nuclear bar is destroyed. We point out that we are studying the molecular gas properties in *only the nuclear region* so we expect to see gas mass fractions on the order of 2% or more.

The molecular gas content of the galaxies for which we have detections are in agreement with the model requirements and are discussed elsewhere (Petitpas & Wilson 2002; Leon, Combes, & Friedli 2000; Sakamoto et al. 1999). We will focus our attention here on the galaxies where we have failed to detect a strong molecular gas component. These are the galaxies that are difficult to explain in light of the current models of double barred galaxies.

As mentioned in §3, the galaxies where we have not detected any CO emission are in general less well studied. As such, we are not able to find direct measurements of the masses of all the galaxies in our sample in the literature. We have estimated the mass for these galaxies from their blue magnitude ($m_{B(T)}$ in de Vaucouleurs et al. 1991). Table 4 shows the apparent blue magnitudes for our sample of galaxies, the absolute magnitude, and the luminosity in solar luminosities. Independent measurements for the masses of some galaxies in our sample exists in the literature. Rubin (1980) determined the dynamical mass of the disk (the dominant source of the blue light) of NGC 5728 to be $\sim 8 \times 10^{10}$ $M_\odot$; Marquez & Moles (1993) find the mass of NGC 6951 to be 1.3×10^{11} $M_\odot$; Smith et al. (1991) determine the mass of NGC 4736 to be 4×10^{10} $M_\odot$. These masses are in acceptable agreement with our estimates considering the uncertainties associated with our technique. It seems, though, that our method is underestimating the galaxy mass by a factor of 2 to 4, which is likely the result of the blue light missing much of the older, redder stellar population of stars in these galaxies. Our estimate therefore provides a lower limit to the true galaxy mass and thus an upper limit to the gas mass fraction.

The limits on the molecular gas masses for the undetected galaxies in our sample range from as high as 3×10^7 $M_\odot$(for NGC 2859) down to 7×10^6 $M_\odot$ for NGC 4371. Using the galaxy masses shown in Table 4, this corresponds to a molecular gas mass fraction of 0.07% and 0.05% for NGC 2859 and NGC 4371, respectively. These low gas mass fractions suggest that some of these galaxies do not contain enough molecular gas to be able to support the nuclear bars observed in the models of Friedli & Martinet (1993) and Shaw et al. (1993).

There are four possible explanations that can bypass this potential problem. The first possibility is that the molecular gas is not confined to the nuclei of these galaxies. A circumnuclear CO morphology is seen in other galaxies (e.g., NGC 7331; Sheth 2000), so it is possible that the molecular gas is outside of the inner 29″ covered by the NRAO beam for the seemingly gas deficient galaxies in our sample. We will need CO observations over a larger area in order to determine if this is the case, but the models of Friedli & Martinet (1993) still require that the inner kpc contain at least 2% gas. If we assume similar disk and bulge profiles for NGC 2859 as those adopted for NGC 5728 by Rubin (1980), we estimate that roughly one tenth of the stellar mass (bulge + disk) is contained in the inner 29″ of NGC 2859. This translates into a gas to mass ratio of *0.7% for the inner 3 kpc* of NGC 2859, so the lack of CO in this galaxy is still a problem for the Friedli & Martinet (1993) model. Even if the gas is located in a large ring beyond our NRAO 12-m beam, it will be part of the main disk and will not have much of an impact on the cooling of the nuclear regions. The failure of the large beams of the H I studies to detect any gas in NGC 2950, NGC 4340, or NGC 4371 suggests that the entire disks of these galaxies are very gas poor.

Another possibility is that the gas in our galaxies is not in molecular form. The gaseous components of the models are basically a dissipation mechanism that acts to prevent the stellar components from being dynamically heated. Models of these galaxies generally treat this gas as being primarily molecular, contained in regions of high density and low filling factor (e.g., Combes & Gerin 1985). Molecular gas also has a higher cooling capacity, since it contains many more emission lines available to it compared to atomic gas. It would

take much more H I gas to dissipate as much energy as molecular gas. We have searched the literature for H I observations of these four galaxies that are undetected in CO. Only NGC 2859 has been detected in H I by various authors (Bieging & Biermann 1977; Giovanardi, Krumm, & Salpeter 1983; Wardle & Knapp 1986; Eskridge & Pogge 1991). An H I mass of 2×10^8 $M_\odot$ was determined by Bieging & Biermann (1977) for the entire disk of NGC 2859, which corresponds to a gas mass ratio of 0.5% *globally*, which is still less that required by the models of Friedli & Martinet (1993) and Shaw et al. (1993). Additionally, 60 μm and 100 μm fluxes suggest global star formation rates less than 0.1 $M_\odot$/year (Eskridge & Pogge 1991; Kennicutt 1998), supporting the claim that these galaxies are gas deficient.

The third possibility is that the NIR isophote twists are not correlated with the gas properties at all. It is possible that the NIR isophote twists are caused by a triaxial stellar bulge, as originally proposed by Kormendy (1979). In this scenario, the lack of molecular gas is not a problem, because there is not much molecular gas in the bulges of galaxies anyway. Evidence against the triaxial bulge model is discussed in Paper I where the existence of a nuclear molecular feature that aligns with the isophote twists supports the existence of a true nuclear bar in the disk of NGC 2273. In addition, detailed analysis of the NIR isophotes indicates that the variations in position angle and bar ellipticity observed in some galaxies cannot be the result of triaxial stellar bulges, but must be produced by nuclear stellar bars (Jungwiert, Combes, & Axon 1997). Observations of deprojected nuclear bar/primary bar offset angles have also ruled out the possibility that the isophote twists are the result of collections of stars trapped in x_2 orbits (Friedli & Martinet 1993).

Finally, if the NIR isophote twists are caused by nuclear stellar bars, but we do not see a significant gas mass fraction in the nucleus, our observations thus favor models that can produce nuclear stellar bars without a molecular gas counterpart. Recently, Maciejewski & Sparke (2000) have discovered a small family of orbits that are capable of sustaining nuclear stellar bars. In light of the lack of gas in some of the galaxies discussed here, we believe that of all models so far, this is the most promising explanation for these instances of double barred galaxies.

It is possible that different mechanisms are at work in different galaxies, and they need to be studied on a case by case basis to determine if the isophote twists are the result of a nuclear bar or a triaxial stellar bulge. In either case, we will need either more sensitive arrays or a sub-millimeter interferometer in the southern hemisphere in order to obtain high resolution CO maps for a larger number of these galaxies. Additionally, high resolution studies of the star formation histories of these galaxies will help determine which stage these galaxies occupy in the evolution of double-barred galaxies.

4. Summary

In an attempt to find double barred galaxies that are bright in CO emission, we have obtained ^{12}CO J=2−1 spectra for nine galaxies with the NRAO 12-m Telescope. In the cases where no emission was found with the NRAO 12-m, we obtained higher resolution ^{12}CO J=3−2 and J=2−1 spectra with the James Clerk Maxwell Telescope. There is only one additional detection in the JCMT spectra of these galaxies despite reaching sensitivities of 4 mK ($T_A^\star$). We detect emission in five of these galaxies. All five galaxies detected exhibit some form of nuclear activity, while the galaxies that were not detected are quiescent and show no signs of any nuclear activity. Thus, within our small sample, the CO emission seems to be detected predominantly in galaxies that harbor some form of nuclear activity (e.g. Seyfert, LINER). We note that the quiescent galaxies are less well studied than the active galaxies in our sample, so it may be that they harbor some form of nuclear activity that has yet to be discovered.

Some models of double barred galaxies suggest that they should be gas rich in order provide a means of dissipating energy that would otherwise heat the stellar population and subsequently destroy the nuclear bars. We use the CO fluxes to estimate the amount of molecular gas in the centers of these galaxies and we find gas masses that range from 7×10^6 $M_\odot$ to more than $\sim 10^9$ $M_\odot$.

The lack of CO and H I detections places very strict limits on the amounts of gas in these galaxies. For some galaxies, there must be less than

a few $\times 10^6$ $M_\odot$ of molecular gas, which (assuming these galaxies are typical disk galaxies) corresponds to gas mass fractions of 0.05 to 0.8% (depending on the assumed mass distribution). These very low gas mass fractions suggest that, contrary to many models, *large amounts of molecular gas are not required* to sustain double-bars in the nuclei of some galaxies.

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Fig. 1.— ^{12}CO J=2−1 spectra taken at the NRAO 12-m of a sample of galaxies with NIR isophote twists and thought to contain double bars. The spectra cover the inner 29″ regions of the galaxy nuclei, which are predicted to be gas rich by the models of Shaw et al. (1993) and Friedli & Martinet (1993). The type of nuclear activity exhibited is shown after the galaxy name (S2 = Seyfert 2; L = LINER). Note that we detect CO emission primarily from galaxies with some form of nuclear activity. The large tick marks on the velocity axis correspond to 500 km s^{-1} intervals, while the smaller tick marks are every 100 km s^{-1}. Higher recession velocities are to the right.

Fig. 2.— ^{12}CO J=2−1 and ^{12}CO J=3−2 spectra taken at the JCMT of a sample of galaxies thought to contain double bars. The J=2−1 spectra cover the inner 21″ while the J=3−2 spectra cover 14″. Note that despite the rather low noise, we do not detect any emission from these four galaxies.

Fig. 3.— JCMT ^{12}CO J=2−1 spectra from Paper II of three galaxies where the ^{12}CO J=2−1 detections with the NRAO were not convincing (see Figure 1).

Table 1
Galaxy Parameters

Galaxy	α (2000)	δ (2000)	$V_{\rm lsr}$ (km s^{-1})	D_{75} (Mpc)	scale (pc/$''$)	RC3	companion?
NGC 2273	$6^h50^m09\overset{s}{.}8$	$+60°50'49''$	1870	25	120	SB(r)a	NGC 2273B
NGC 2859	$9^h24^m19\overset{s}{.}5$	$+34°30'43''$	1687	22	110	(R)SB(r)0	no
NGC 2950	$9^h42^m35\overset{s}{.}1$	$+58°51'05''$	1337	18	87	(R)SB(r)0	no
NGC 3081	$9^h59^m30\overset{s}{.}6$	$-22°49'41''$	2385	32	160	(R_1)SAB(r)0/a	no
NGC 4340	$12^h23^m35\overset{s}{.}8$	$+16°43'16''$	950	13	63	SB(r)0	NGC 4350?
NGC 4371	$12^h24^m55\overset{s}{.}5$	$+11°42'10''$	943	13	63	SB(r)0	no
NGC 4736	$12^h50^m53\overset{s}{.}4$	$+41°07'02''$	308	4	19	(R)SA(r)ab	no
NGC 5728	$14^h42^m23\overset{s}{.}8$	$-17°15'03''$	2788	37	180	(R_1)SAB(r)a	no
NGC 5850	$15^h07^m07\overset{s}{.}5$	$+1°32'43''$	2556	34	160	SB(r)b	NGC 5846
NGC 6951	$20^h37^m11\overset{s}{.}6$	$+66°06'12''$	1424	19	92	SAB(rs)bc	no

Note.—All distances are taken from the NASA-IPAC Extragalactic Database (NED) and assume a Hubble Constant of 75 km s^{-1} (Mpc)$^{-1}$.

Table 2
Observing Parameters

Galaxy	Line (^{12}CO)	Tele.	$t_{\rm int.}$ (h:m)	$T_{\rm sys}$ (K)	r.m.s.[a] (mK $T_{\rm MB}$)
NGC 2273	J=2−1	NRAO	1:46	516	16
···	J=2−1	JCMT	0:30	322	8
NGC 2859	J=2−1	NRAO	1:58	467	14
···	J=3−2	JCMT	2:20	630	6
NGC 2950	J=2−1	JCMT	0:30	254	6
NGC 3081	J=2−1	NRAO	2:09	1012	28
···	J=2−1	JCMT	2:20	463	7
NGC 4340	J=2−1	NRAO	1:58	199	13
···	J=3−2	JCMT	2:00	485	5
NGC 4371	J=2−1	NRAO	1:58	511	15
···	J=3−2	JCMT	2:00	503	5
NGC 4736	J=2−1	NRAO	0:35	468	25
NGC 5728	J=2−1	NRAO	1:58	605	18
···	J=2−1	JCMT	0:50	467	9
NGC 5850	J=2−1	NRAO	1:58	453	13
NGC 6951	J=2−1	NRAO	3:20	424	10

[a]Given for a velocity resolution of 10 km s^{-1} which corresponds to 7.68 MHz at 230 GHz and 11.5 MHz at 345 GHz.

Table 3
CO Fluxes and Molecular Gas Masses

Galaxy	V limits (km s^{-1})	Transition (tele.) (^{12}CO)	Flux[a] (K km s^{-1} T_{MB})	r_{int}[b] (kpc)	Gas Mass ($M_\odot$)
NGC 2273	1600-2020	J=2−1 (NRAO)	9.8 ± 1.0	1.7	8.2×10^8
···	···	J=2−1 (JCMT)	19.7± 0.5	1.3	1.3×10^9
NGC 2859	1490-1890	J=2−1 (NRAO)	(2.6 ± 0.9)	1.6	(2.0×10^8)
···	···	J=3−2 (JCMT)	< 0.40	0.8	$< 2.9 \times 10^7$
NGC 2950	1140-1540	J=2−1 (JCMT)	< 0.33	0.9	$< 1.5 \times 10^7$
NGC 3081	2200-2550	J=2−1 (NRAO)	(3.6 ± 1.8)	2.3	(6.2×10^8)
···	···	J=2−1 (JCMT)	4.6 ± 0.3	1.7	6.5×10^8
NGC 4340	750-1150	J=2−1 (NRAO)	(2.8 ± 0.8)	0.9	(8.1×10^7)
···	···	J=3−2 (JCMT)	< 0.32	0.4	$< 7.7 \times 10^6$
NGC 4371	740-1140	J=2−1 (NRAO)	< 1.0	0.9	$< 2.7 \times 10^7$
···	···	J=3−2 (JCMT)	< 0.29	0.4	$< 7.0 \times 10^6$
NGC 4736	100-450	J=2−1 (NRAO)	61.7 ± 1.4	0.3	1.7×10^8
NGC 5728	2500-3050	J=2−1 (NRAO)	7.4 ± 1.3	2.6	6.1×10^8
···	···	J=2−1 (JCMT)	24.6 ± 0.6	1.9	1.7×10^9
NGC 5850	2400-2650	J=2−1 (NRAO)	6.9 ± 0.7	2.3	1.3×10^9
NGC 6951[c]	1250-1620	J=2−1 (NRAO)	13.4 ± 0.6	1.3	9.7×10^8

Note.—For calculating gas masses for NGC 2273, NGC 5728, NGC 6951 we adopt CO J=2−1/J=1−0 ratios of 0.88, 1.96, and 0.59 respectively (Petitpas & Wilson 2003). For the other galaxies we have assumed a ^{12}CO J=2−1/J=1−0 ratio of 0.7 and (where necessary) a J=3−2/J=2−1 line ratio of 1, similar to the values found for other double barred galaxies (Petitpas & Wilson 2003). The flux values for the questionable detections (where the integrated intensities are larger than three times the noise associated with that region) are enclosed in parentheses.

[a]The beam size for the NRAO 12-m at CO J=2−1 is 29″. The beam size for the JCMT is 21″ at CO J=2−1 and 14″ at J=3−2.

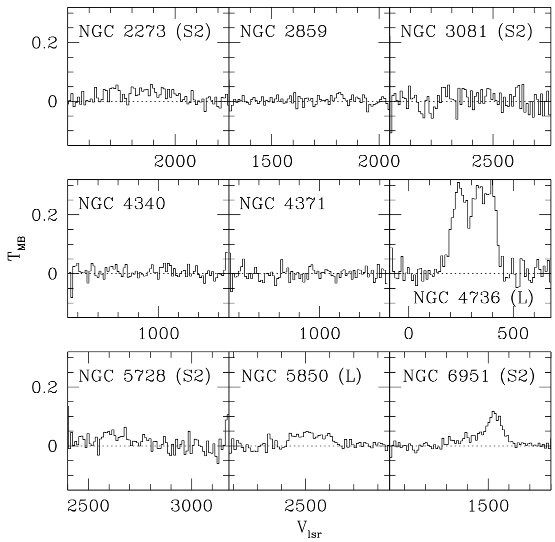
[b]The radius interior to which the flux/mass has been measured.

[c]The pointing may have been off; see text for details.

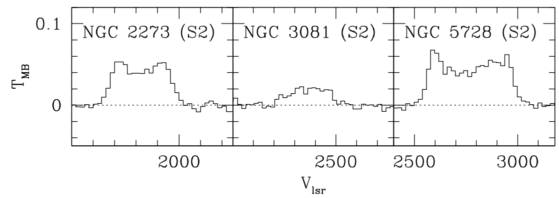
Table 4
Galaxy Masses Estimated from Blue Light

Galaxy	$m_{B(T)}$ (app.)	M_B (abs.)	L_B ($L_\odot$)	Mass ($M_\odot$)
NGC 2273	12.55	−19.44	8.7×10^9	2.6×10^{10}
NGC 2859	11.83	−19.87	1.3×10^{10}	3.9×10^{10}
NGC 2950	11.84	−19.44	8.7×10^9	2.9×10^{10}
NGC 3081	12.85	−19.68	1.1×10^{10}	3.3×10^{10}
NGC 4340	12.10	−18.47	3.6×10^9	1.1×10^{10}
NGC 4371	11.79	−18.78	4.7×10^9	1.4×10^{10}
NGC 4736	8.99	−19.02	5.9×10^9	1.8×10^{10}
NGC 5728	12.57	−20.27	1.9×10^{10}	5.7×10^{10}
NGC 5850	11.54	−21.18	4.3×10^{10}	1.3×10^{11}
NGC 6951	11.64	−19.75	1.2×10^{10}	3.6×10^{10}

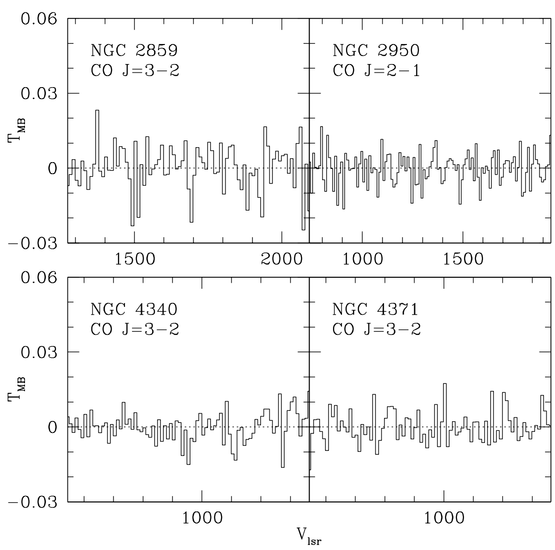
Note.—$m_{B(T)}$ is the apparent blue magnitude of the galaxy extrapolated to infinite radius (RC3). We adopt +5.41 for the Suns absolute blue magnitude (Allen 1964) and note that a change of ∼0.3 in the galactic magnitude would result in a factor of ∼2 variation in the luminosity. The last column assumes a mass to light ratio of 3, which is typical for barred spiral galaxies (Forbes 1992).



NGC 2273 (S2)
NGC 2859
NGC 3081 (S2)
NGC 4340
NGC 4371
NGC 4736 (L)
NGC 5728 (S2)
NGC 5850 (L)
NGC 6951 (S2)
T_MB
V_lsr



NGC 2273 (S2)
NGC 3081 (S2)
NGC 5728 (S2)
T_MB
V_lsr



NGC 2859
CO J=3−2
NGC 2950
CO J=2−1
NGC 4340
CO J=3−2
NGC 4371
CO J=3−2
T_MB
V_lsr